# STRENGTH PREDICTION AND DURABILITY PERFORMANCE OF CONCRETE CONTAINING COAL BOTTOM ASH AS SUPPLEMENTARY CEMENTITIOUS MATERIAL UNDER AGGRESSIVE ENVIRONMENT

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## ABSTRACT

Strength prediction and durability of concrete under aggressive environment requires serious attention for all kind of significant concrete structures. However, concrete built with Ordinary Portland Cement (OPC), when exposed to the aggressive environment tends to deteriorate much faster than their projected service life. Therefore, Supplementary Cementitious Material (SCM) need to be introduced to improve the strength and durability performance of concrete. Besides that, prediction of concrete compressive strength is also an important aspect for the safety and quality control of concrete structures. Thus, this study aims to evaluate strength and durability performance of concrete containing Coal Bottom Ash (CBA) as a SCM and to develop empirical equation to predict compressive strength of concrete under normal as well as in aggressive environment. CBA was considered as SCM because it is a huge waste that produced by a coal-based power plants, which creates environmental problems for the global society. Initially, raw CBA was grinded for various periods, to get different particle fineness, then CBA was incorporated as replacement of OPC in concrete at various percentages 10%, 20% and 30% by weight of cement. The optimum percentage replacement and suitable grinding period were determined based on concrete strength performances and it was found that 10% proportion of CBA gives the optimum results at the age of 28 days. Next, the performance of concrete containing 10% CBA was further evaluated in terms of compressive strength, change in weight and degree of damage under aggressive environment such as 5% sodium sulphate ($Na_2SO_4$), 5% sodium chloride (NaCl), combination of both (5%$Na_2SO_4$+5%NaCl) and seawater at the exposure period of 28, 56, 90 and 180 days. Additionally, microstructural changes in concrete due to aggressive environment were also assessed through Scanning Electron

Microscopy (SEM) and X-Ray Diffraction (XRD) techniques. Besides that, the durability performance of concrete containing CBA were also evaluated using Rapid Chloride Permeability Test (RCPT). Moreover, influence of CBA on the drying shrinkage of concrete was also evaluated up to age of 180 days. The experimental results reveal that Control Mix (CM) delivers worst performance when exposed to seawater. However, the incorporation of 10% CBA in concrete enhances its strength performance under seawater exposure. Strength performance of concrete containing 10% CBA exhibits satisfactory in all aggressive environment conditions except 5% NaCl. It was also evaluated that concrete containing 10% CBA exhibits around 45.4% reduction in chloride penetration as compared to CM at 180 days, which indicated its potentiality as durable SCM. Besides that, it was experimentally and theoretically verified that the proposed Bolomey's Modified Equation (BME) can be used for the prediction of compressive strength of concrete containing ground CBA exposed to normal as well as aggressive environment that particularly represents the marine environment. Hence, this study declared 10% ground CBA as optimum that can be used for future research.

**ABSTRAK**

Ramalan kekuatan dan ketahanan konkrit di bawah persekitaran agresif memerlukan perhatian yang serius terhadap semua jenis struktur konkrit yang penting. Bagaimanapun, konkrit yang dibina dengan simen Portland Biasa (OPC), apabila terdedah kepada persekitaran yang agresif cenderung merosot lebih cepat daripada kehidupan perkhidmatan yang diunjurkan. Oleh itu, matlamat kajian ini adalah bertujuan untuk menggunakan CBA sebagai bahan ganti simen dalam konkrit dan untuk menilai kekuatan serta ketahanlasakan konkrit di bawah persekitaran agresif. Sebelum digunakan, CBA telah dikisar dengan tempoh yang berbeza iaitu 20 dan 30 jam untuk mendapatkan kehalusan zarah yang berbeza berbanding dengan simen Portland biasa (OPC). CBA telah digunakan sebagai bahan ganti simen dalam konkrit pada kadar 10%, 20% dan 30% daripada berat simen. Peratusan gantian optimum CBA telah ditentu berdasarkan prestasi konkrit seperti kebolehkerjaan, kekuatan mampatan, kekuatan terikan dan kekuatan lenturan. Daripada ujikaji awal dapat ditentukan bahawa kadar gantian CBA sebanyak 10% telah memberikan keputusan yang optimum pada usia 28 hari. Dengan peratusan optimum ini, ujikaji terhadap prestasi konkrit iaitu kekuatan mampatan, perubahan berat dan darjah kerosakan konkrit dalam persekitaran agresif iaitu 5% natrium sulfat ($Na_2SO_4$), 5% natrium klorida (NaCl), gabungan kedua-duanya (5 % $Na_2SO_4$ + 5% NaCl) dan air laut pada tempoh pendedahan 28, 56, 90 dan 180 hari telah dijalankan. Selanjutnya, perubahan mikrostruktur dalam konkrit akibat persekitaran agresif telah dinilai melalui teknik pengimbasan mikroskop elektron (SEM) dan teknik difraksi sinar-X (XRD). Selain itu, ketahanlasakan konkrit yang mengandungi CBA juga dinilai terhadap kebolehtelapan cepat klorida (RCPT). Selain itu, pengecutan keringan konkrit yang mengandungi CBA juga diukur sehingga usia 180 hari pada suhu bilik. Hasil eksperimen menunjukkan bahawa campuran kawalan (CM) menyampaikan prestasi terburuk apabila terdedah kepada air laut. Walau bagaimanapun, penggabungan 10% CBA dalam konkrit meningkatkan prestasi kekuatan di bawah pendedahan air laut. Prestasi kekuatan konkrit yang mengandungi 10% CBA mempamerkan tahap memuaskan dalam semua keadaan persekitaran yang agresif kecuali 5% NaCl pada tempoh pendedahan 180 hari. Ia juga menilai konkrit yang mengandungi 10% CBA mempamerkan sekitar 45.4% pengurangan penembusan klorida berbanding CM pada 180 hari, yang menunjukkan potensinya sebagai SCM tahan lama. Di samping itu, ia adalah secara eksperimen dan teorinya mengesahkan yang dicadangkan Persamaan Modified Bolomey (BME) boleh digunakan untuk ramalan kekuatan mampatan konkrit yang mengandungi tanah CBA yang terdedah kepada persekitaran yang normal dan juga agresif yang mewakili persekitaran laut. Oleh itu, kajian ini mengisytiharkan 10% tanah CBA sebagai optimum yang boleh digunakan untuk penyelidikan masa depan.

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## LIST OF SYMBOLS AND ABBREVIATIONS

| | | |
|---|---|---|
| *ACI* | - | American Concrete Institute |
| *ASTM* | - | American Society for Testing and Materials |
| BME | - | Bolomey’s Modified Equation |
| *BS* | - | British Standard |
| *CBA* | - | Coal Bottom Ash |
| *CFA* | - | Coal Fly Ash |
| *EN* | - | European Standard |
| *LOI* | - | Loss on Ignition |
| *MPa* | - | Mega Pascal |
| *MS* | - | Malaysian Standard |
| *OPC* | - | Ordinary Portland cement |
| *RCPT* | - | Rapid Chloride Penetration Test |
| *SCM* | - | Supplementary Cementitious Material |
| *SEM* | - | Scanning Electron Microscope |
| *XRF* | - | X-Ray Fluorescence |
| *XRD* | - | X-Ray Diffraction |
| $\alpha$ | - | Alpha |

| | | |
|---|---|---|
| $\beta$ | - | Beta |
| $\sum$ | - | Sigma, sum of all values |
| °C | - | Degree Celsius |
| $f_{cu}$ | - | Compressive Strength |
| $f_f$ | - | Flexural Strength |
| $f_t$ | - | Splitting Tensile Strength |
| *kg* | - | Kilogram |
| mm | - | Millimeter |
| ppm | - | Parts Per Million |
| $Al_2O_3$ | - | Aluminium Trioxide |
| *CaO* | - | Calcium Oxide |
| $CO_2$ | - | Carbon Dioxide |
| *NaCl* | - | Sodium Chloride |
| $Na_2SO_4$ | - | Sodium Sulphate |
| $SiO_2$ | - | Silica dioxide |
| $SO_3$ | - | Sulfur trioxide |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of Study

Concrete is one of the significant materials in construction works, around 2.7 billion cubic meters of concrete was produced in 2002 worldwide, which is more than 0.4 cubic meters of concrete generated per person per year and it is expected that the demand of concrete will touch to 7.5 billion cubic meters (about 18 billion tons) a year by 2050 (Rafieizonooz *et al.*, 2016). Such massive application of concrete raises the demand for ordinary Portland cement (OPC) which is the main constituent in concrete production. In addition to that it was also mentioned by Ramos *et al.* (2013) that every year more than one cubic meter of concrete is produced per person globally with OPC being key ingredient, which creating the greatest environmental problem in terms of carbon dioxide emissions. Currently around 3 billion tons of OPC are consumed globally and for every 600 kg of cement, around 400 kilograms of carbon dioxide ($CO_2$) gas is released, which is around 5–8% input of all man made $CO_2$ (Flatt, Roussel, & Cheeseman, 2012). The solution for that pollution is utilizations of industrial by-products like fly ash, bottom ash, slag, waste glass, etc. in concrete production (Yuksel & Bilir, 2007; Ghafoori & Bucholc, 1996; Topcu & Canbaz, 2004), These advanced practices in the field of concrete engineering could reduce the cost of construction, overcome environmental problems and enhance durability of concrete (Yuksel, Bilir, & Ozkan, 2007). However, the coal based thermal power plants have produced tremendous amount of coal bottom ash (CBA) and coal fly ash (CFA) throughout a year. The annual productions of CBA in India around 25 million tons (Singh & Siddique, 2015), United State is 14 million tons, Europe about 4 million tons (Kim, 2015) and in Malaysia about 1.7 million tons (Rafieizonooz *et al.*, 2016). The proper handling of such huge volume of CBA waste is a challenging job and it is also an important global environmental concern (Rafieizonooz *et al.*, 2016). Therefore, it is necessary to utilize CBA in the field of construction to resolve this environmental issue. The CBA is larger particle size and higher porosity as compared to fly ash and its size is almost similar to the natural sand, therefore, many researchers have been utilizing CBA as a sand replacement material in concrete (Wongkeo & Chaipanich, 2010). But the utilization of CBA as a cement replacement is not broadly used, although it has enough amount of silica which indicates its pozzolanic potentiality. However, healthy pozzolanic activity of CBA is an indication of later age strength development in the concrete. Such factors increase the tendency among the researchers to explore the application of ground CBA as alternative cementitious material for sustainable construction to considerably reduce the consumption of ordinary Portland cement. Therefore, it is necessary to extend the research to study on the opportunity of converting waste materials into a useful product for the benefits of human civilization. Hence, it is essential to adopt waste to wealth approach in the construction sector and utilize industrial waste by-products as supplementary cementitious material (SCM).

Considering the industrial waste utilization in concrete, strength and durability aspects are the important concern, because concrete structures made from Ordinary Portland Cement (OPC), when exposed to the aggressive environment; tends to deteriorate much faster than their projected service life (Okoye e*t al.*, 2017). Concrete structure built with OPC having two major issues of durability and sustainability. To build the green, durable and sustainable concrete structures, SCM need to be explored for the improvement of durability performance of concrete. However, there are two major environmental benefits of using CBA as supplementary binder over the OPC; firstly, considerable reduction in greenhouse gases emissions and secondly, reduction in solid waste production through coal fired thermal power plants. Moreover, it was suggested by Zhao *et al.* (2015) and Ramadhansyah *et al.* (2011) that strength of concrete can be improved by utilizing SCM. However, previous research also declared that the finer the size of SCM, the higher the pozzolanic activity and hydration rate (Zhao *et al.*, 2015). Therefore, to make better use of CBA, it could typically develop through mechanical grinding process to achieve fine particles size.

The selection of SCM should be such that it could deliver strength and durability performance and considered as environmental-friendly. It was stated by Pyo & Kim (2017) that considering the environmental concern, two different means have been suggested: (1) expansion of new materials, which poses high strength and durability and (2) establishment of such materials which required less energy for the preparation through industrial by-products. However, it is debatable issue that strength and durability of concrete containing SCM over the OPC (Okoye *et al.*, 2017). Therefore, the CBA utilization has long been known as a fine aggregate replacement material for normal strength concrete. The review of literature starting from the early days till now suggests that there is no any systematic study is available on strength and durability performance of concrete containing CBA as SCM. In the view of sustainable development, it is imperative to use SCM in place of OPC in the field of concrete construction. Considering the previous findings regarding concrete performance under aggressive environment, the aim of this research study has been set-forward to investigate the effect of CBA as SCM on the concrete performance under aggressive environment that represents the marine environment.

## 1.2 Problem statement

Strength and durability are major issues for concrete structures around the globe (Maes & Belie, 2014). It is well known that corrosions in reinforced concrete due to ingress of chloride ions, which affects the durability of concrete structures. Such effect is common in concrete structures exposed to the marine environment (Otieno, Beushausen, & Alexander, 2016). Once chloride has been accumulated on the surface of steel bars embedded in the concrete, pitting corrosion will happen. If concrete cover is not deteriorated, the diffusion of chloride ion into concrete is very slow. When concrete cover become spoiled by sulphate attack, which is common in concrete constructions, then chloride ion will quickly access to the surface of steel reinforcement in concrete

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